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Sustainability considerations for electricity generation from biomass

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ABSTRACT

The sustainability of electricity generation from biomass has been assessed in this work according to the key indicators of price, efficiency, greenhouse gas emissions, availability, limitations, land use, water use and social impacts. Biomass produced electricity generally provides favourable price, efficiency, emissions, availability and limitations but often has unfavorably high land and water usage as well as social impacts. The type and growing location of the biomass source are paramount to its sustainability. Hardy crops grown on unused or marginal land and waste products are more sustainable than dedicated energy crops grown on food producing land using high rates of fertilisers.

Contents

1. Introduction

The generation of electricity has become one of the key technological advancements linked to high quality of life in modern society. As global populations increase and third world nations

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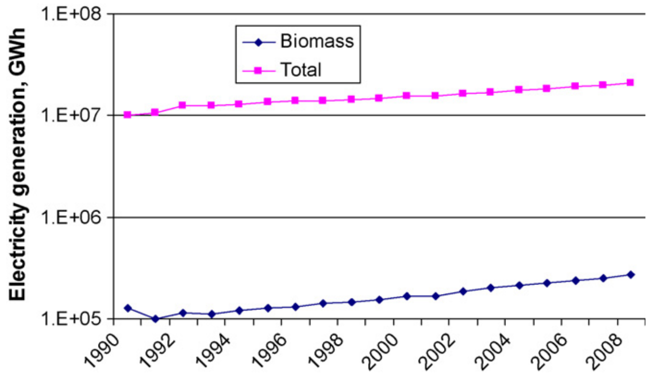

Fig. 1. Biomass and total world electricity generation time trend (Euromonitor International, 2009) [1].

develop, electricity demand continues to grow. Energy security is a matter of global significance, energy sources need to be available in constant supply and at low cost. Significant attention is also focused on the environmental impacts of electricity generation as high polluting technologies attract public outrage. As information comes to light about the damaging health and environmental effects of the conventional methods of electricity generation, alternate approaches are being sought. With limited fossil fuel reserves and their volatile prices, renewable fuels can provide increased energy security and stable price profiles.

Biomass is organic, plant derived material that may be converted into other forms of energy. It is easily produced in almost any environment, regenerated quickly and has a long history of use for direct heating applications. Biomass is the only fuel available for renewable, combustion based electricity generation. For these reasons, it has gained significant attention as a substitute for fossil fuels.

The use of biomass to produce electricity has steadily increased by an average of 13 TWh per year between 2000 and 2008. Biomass based electricity has maintained its market share of total global generation over the last 20 years, at approximately 2%. This is shown in Fig. 1 [1].

The use of biomass is widespread, as shown in Fig. 2 [1]. There are a total of 62 countries in the world currently producing electricity from biomass [1]. The USA is the dominant biomass electricity producer at 26% of world production, followed by Germany (15%), Brazil and Japan (both 7%).

Biomass could help to ensure global energy security (primary concern) and help to mitigate carbon pollution (secondary

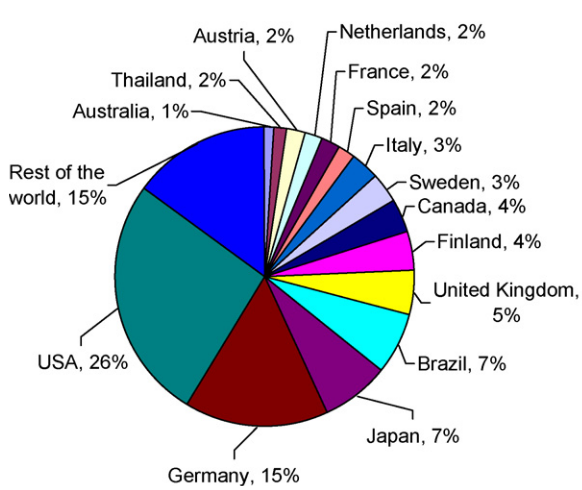

Fig. 2. Global distribution of biomass energy use in 2008 (Euromonitor International, 2009) [1].

concern) [2]. Maintaining a primary focus on energy security could have economic impacts, where some price premium is considered appropriate for such security.

To understand the potential of biomass to contribute more significantly to global electricity generation, a full assessment of its potential for sustainable development should be conducted. Previous studies have included detailed investigations on the optimisation of crop growth and processing [3,4], variability of biomass availability and costs between countries [5] and the performance of specific types of biomass between different technologies [6]. A large number of studies have assessed the potential of biomass based power generation for offsetting fossil fuel carbon emissions [7–9]. Accordingly, there is a significant knowledge base established, however, the information has not yet been collected for a full sustainability assessment. This study will review the information from the previous studies to assess the environmental, social, engineering and financial sustainability of biomass use in electricity generation.

2. Technologies

There are three primary technology categories used for the combustion based conversion of biomass into electricity. Each category has undergone significant development and therefore has many different methods available.

2.1. Pyrolysis

Pyrolysis is the thermal destruction of biomass in an anaerobic environment, without the addition of steam or air to produce gases and condensable vapours [10]. Combustion of these gases occurs in a gas turbine, typically combined cycle [11].

2.2. Gasification

In gasification, biomass is partly oxidised by controlling oxygen by the addition of steam to produce combustible gases, which have a high calorific value [10]. Product gases are fed into a combined cycle gas turbine power plant [12].

2.3. Direct combustion

Direct combustion is the complete oxidation of biomass in excess air, to produce carbon dioxide and water. Hot flue gases are used to heat process water to steam, which drives a turbine, typically via a Rankine cycle [10].

Direct combustion is the oldest and simplest, but most inefficient technology. Gasification and pyrolysis have higher efficiencies, but require significantly more process control and investment.

3. Biomass types

There are many biomass types available for the production of electricity, as shown in Table 1. This discussion is limited to biomass residues and dedicated energy crops. Residues are waste products after a higher value product has been obtained. In the case of bagasse, it is the sugar cane residue once sugar and molasses have been extracted. It can also be the tops and leaves of the sugar cane. Dedicated energy crops are grown exclusively for the purpose of energy production.

3.1. Residues

3.1.1. Bagasse

Bagasse electricity generation is a proven process, taking the waste products generated on-site and re-using them directly to

Table 1
Biomass types.

Residues		
	Agricultural crop and process residues	
		Bagasse
		Other
	Forestry residues	
	Wood wastes	
Dedicated Energy Crops		
	Food competitive	
		Short rotation croppice
	Arid/unusable land	
		Mallee

power the process. There is typically some surplus generated that is sold to the local grid. Waste heat after power generation is typically applied to sugar refining. In this way, costs and transportation are minimal. The inherent linkage provides one of the most sustainable methods of electricity generation available. However, the seasonality of sugar cane harvesting may limit applicability of bagasse as a stand alone product. This limitation does not exist when used solely in conjunction with sugar production as no electricity is required when sugar cane is unavailable.

Sugar cane is produced in over 100 countries worldwide. The main sugar producing countries are shown in Fig. 3 [13]. Brazil is by far the most dominant sugar producing country, accounting for nearly 35% of global production in 2007, followed by India at over 22%. All other countries produce much less, but with many countries such as China, Thailand and Australia still producing considerable amounts. In 2005, over 10^{15} tonnes of bagasse were consumed for power production [13].

3.1.2. Forest and non-bagasse agricultural residues

There are many benefits of using residues for energy production, including redirecting a waste product from landfill [14] and they can be obtained at little or no cost. Available wastes include large amounts of leftover material, such as stalks, prunings, skins, shells and off-cuts from rice, grain, cotton, vegetables and fruit that are not used as agricultural products. However, residues are a low density and low value fuel where transportation costs per unit of energy are high [15]. Additionally, agricultural wastes have limited quantities, they are location specific and not always of the ideal quality for power generation [16].

3.2. Dedicated energy crops

For biomass to play a significant role in the world's energy future, dedicated energy crops are essential. Short rotation energy crops are gaining popularity internationally. Typical crops include poplar, willow, eucalyptus and non-woody perennial grasses, such as *miscanthus*. Crop rotation periods are usually 3–10 years for woody crops, such as willow and poplar [17]. Important issues to be addressed in dedicated energy crops are the depletion of soil nutrients, organic matter and moisture-holding capacity.

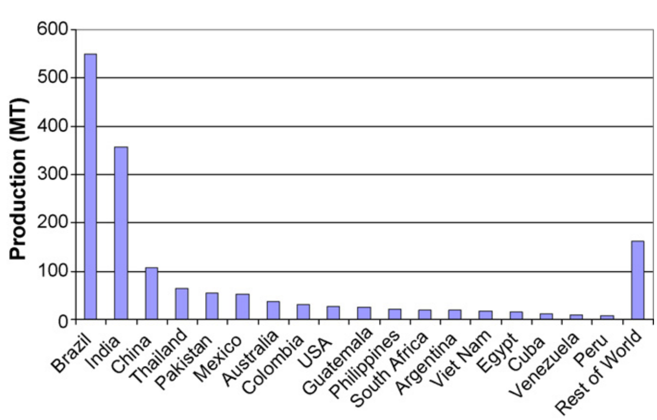

Fig. 3. Sugar cane production by country, 2007 (FAO, 2009) [13].

Ideal biomass characteristics are high yield, low input energy, low cost, composed with least amount of contaminants and with low nutrient, water, pesticide and fertiliser requirements. Essential biomass properties are moisture content, calorific value, percentage fixed carbon and volatiles, ash/residue content, alkali metal content, cellulose to lignin ratio and bulk density [18].

Crops grown solely for their energy content should give good crop yields. Switchgrass and wood from short rotation forestry, such as poplar and willow, are ideally suited as energy crops [19]. Crops such as wheat and corn, require applications of fertiliser, take up prime agricultural land and give low crop yields, making them unsuitable energy crops [19].

One of the key concerns regarding bioenergy crops is the loss of biodiversity. This concern is due to monocultures being less stable than forests and requiring increased energy inputs, such as pesticides and fertilisers, to maintain productivity [20]. To mitigate this issue, IEA Bioenergy [15] suggests retaining patches/riparian corridors of natural vegetation as well as re-establishing native vegetation.

Biomass feedstock yields vary considerably, according to climatic and soil conditions, agriculture and silviculture practices. The competitiveness of biomass is essentially dependent on the development of short rotation croppice and enhanced yields without great cost increases [21]. Heller et al. [22] found that willow biomass crops are sustainable from an energy balance perspective and contribute environmental benefits.

The Clean Energy Council (CEC) [23] found that, unless stationary energy prices and CO_2 taxes increase significantly, dedicated energy crops are unlikely to be economically viable. The CEC [24] also state that dedicated energy crops only make sense in the medium term for combating salinity, land erosion and loss of biodiversity. Dedicated energy crops are less viable than crops with multiple economic benefits. Strezov et al. [25] and Hoogwijk et al. [26] believe that the production of energy crops on abandoned agricultural land and land at rest may allow for large amounts of biomass to be produced at reasonable cost. Koh and Hoi [27] claim there is insufficient surplus agricultural land for dedicated energy crops to meet demand.

4. Sustainability assessment

To conduct this assessment, several key sustainability indicators were identified, the price to produce electricity, efficiency of energy conversion, total carbon dioxide emissions, availability, limitations, water use and social issues. All indicators are assessed over the entire life cycle on a per kilowatt hour basis.

Biomass conversion processes include thermal conversion technologies where the biomass energy is converted to electricity via combustion. Power production from methane emitted due to decomposing landfill and sewage are also considered biomass combustion based electricity.

Significant amounts of biomass are used in co-combustion with coal, typically up to around 15% biomass. Overall, this is not a renewable process and the co-combustion with coal is excluded from discussion in this work.

The most common types of biomass used for electricity production and analysed in this work are agricultural residues, forest residues and dedicated energy crops. Other biomass sources include landfill gas, animal and human waste. However, as plant material is the most common form of biomass used for electricity generation, the other sources will not be discussed in this work.

Table 2
Literature prices for biomass power production.

Author/s	Year	c/kWh (US)	Technology	Size (MW)	Fuel
Ganesh and Banerjee	2001	3.8–10.2	Pyrolysis	5	Energy crops
Bridgwater et al.	2002	9.4	Pyrolysis	20	Wood chip
Elliot	1993	7.8	Gasifier	25	Low cost plantation
Bridgwater	1995	6	Gasifier	60	Wood
Craig and Mann	1996	6.5–8.2	Gasifier	56–132	Wood
Faaij et al.	1997	−7.5 to +9.6	Gasifier	30	Wastes and residues
Faaij et al.	1998	7.7	Gasifier	30	Willow
McKendry	2002	16.4	Gasifier	7.5	Energy crops
Hamelinck et al.	2005	4.2	Gasifier	300	Wood
Gan and Smith	2006	5	Gasifier	10+	Poplar
Braunbeck et al.	1999	4.5–7.1	Combustion	Large	Bagasse
van den Broek et al.	2000	4.9	Combustion	23.4	Bagasse
van den Broek et al.	2001	9.1	Combustion	24	Wood
van den Broek et al.	2002	7.5	Combustion	13.5	Energy crops
Fung et al.	2002	2.8–8.5	Combustion	10	Wood
Bain and Overend	2002	8–12	Combustion	20	Mixed
Gustavsson and Madlener	2003	4-6.5	Combustion	50–100	Logging residues
Gustavsson and Madlener	2003	3.9–6.9	Combustion	50–100	Logging residues
Kumar et al.	2003	6.3	Combustion	137	Forest harvest residues
Kumar et al.	2003	5	Combustion	450	Agricultural residues
Kumar et al.	2003	4.7	Combustion	450+	Whole forest harvesting
Bakos et al.	2008	12.7	Combustion	2+	Agricultural residues
Alonso-Pippo et al.	2008	6	Combustion	600	Bagasse
Blanco and Azqueta	2008	9.3–12.4	Combustion	25	Straw
Kumar et al.	2008	5.4–5.9	Combustion	240	Trees killed by pine beetle

The sustainability assessed here considers the entire life cycle, from biomass growth, collection and transportation to power production and waste disposal. Power plant life times are assumed as 20 years.

4.1. Price

4.1.1. Total cost of electricity production

Variability in feed materials and processing technologies results in large biomass price variations, shown in Table 2 [5,8,11,28–45]. Lowest values are seen for waste materials with little or no cost and minimal transportation requirements. Due to the low energy density (energy yield per hectare) of most biomass and high costs of transport from gathering site, any transportation significantly affects the resulting feedstock cost [41]. A high biomass density is therefore essential to profitability. Biomass quantities and costs vary with fluctuating harvests, increased utilisation by competitors and transportation [47].

There is wide debate on the cost effectiveness and major influences on price. Bridgwater [33] claims that the economics lie in low cost waste or fiscal incentives regardless of scale, as opposed to Siewert et al. [48] who state that 50–100 MW plants offer greater economy than smaller plants, without the need for financial support. According to Dornburg and Faaij [49] wood waste needs to be provided at zero cost to make profits from electricity generation possible. This agrees with the findings of Ganesh and Banjeree [11] confirming the largest influence on price is the fuel cost. It is in contrast with IEA Bioenergy [15], who found that energy crops are typically low value products and that profitability comes from low production costs.

The negative cost value given by Faaij et al. [38] is for instances where current waste disposal costs can serve as income for the facility. With prices ranging from −7.5 to 16.4 c/kWh and an average price of 6.9 c/kWh, biomass power production is not cost effective at present, where fossil fuel technologies are available for an average of 4.2–4.8 c/kWh. However, according to Sáez et al. [50], when externalities, such as human health, soil erosion, etc. are included, the total price of biomass is cheaper than coal. Hatje and Ruhl [51] state that biomass is the most profitable renewable energy source after hydropower, with respect to total energy and carbon reduction costs. Comparing to the median electricity costs of the remaining renewable electricity technologies shown by Evans et al. [52], biomass is cheaper than photovoltaics (24 c/kWh), approximately equal with geothermal (6.8 c/kWh) but more expensive than wind (6.6 c/kWh) and hydro (5.1 c/kWh).

4.1.2. Investment costs and technology choice

Investment costs for biomass to energy conversion exceed other thermal technologies by a factor of 3–4 due to higher processing volumes and increased handling requirements. The capital intensive nature of biomass technology can deter investment. Also, financing biomass plant construction can be complicated because many conversion technologies are still in pilot scale [23].

When selecting between different technologies, combustion based technologies are more profitable over their life cycle than gasification and pyrolysis, despite higher operating costs [53]. Capital costs for direct combustion are around \$1.9–2.9/kW. For pyrolysis, costs are much higher at \$3.5–4.5/kW, making it one of the most capital intensive electricity generation technologies [54], comparable with nuclear.

4.1.3. Process versus feedstock price

Blanco and Azqueta [31] found that the fuel cost comprised between 56 and 75% of the total price when using straw in Spain.

Gan and Smith [8] found that the non-fuel costs of capital, maintenance and operation of biomass fired electricity generation was nearly the same as the total electricity production cost of coal systems. They also found that the fuel accounted for approximately 50% of the total electricity cost for biomass gasification systems. Biomass procured from logging residues was more cost effective than energy plantations.

Stucley et al. [55] showed that fuel procurement costs can account for some 50–60% of the total bioelectricity production costs. The total delivered fuel cost is typically 25% biomass production and 25% transportation to the power plant, with harvesting accounting for the remaining 50% of the total delivered fuel cost. Accordingly, reductions in fuel costs will improve overall power supply prices.

McIlveen-Wright et al. [56] found that dedicated forestry crop plants handling over 500 dry tonnes per day could be economically

Table 3
The efficiency of energy conversion from biomass to electricity.

Author/s	Year	% Efficiency	Comment
Craig and Mann	1996	35.4–39.7	Gasifier
Gustavsson	1997	36	Combustion
Faaij et al.	1997	35.4–40.3	Gasifier
Bain et al.	1998	35	
Stahl and Neergaard	1998	32	Gasifier
Chum and Overend	2001	17.2	Gasifier
Berndes	2001	20–25	Combustion
Ganesh and Banerjee	2001	26	Combustion
Ganesh and Banerjee	2001	40	Combustion
Ganesh and Banerjee	2001	28	Gasifier
Ganesh and Banerjee	2001	31	Pyro lysis
Bain and Overend	2002	20	
IEA Bioenergy	2002	25	5–10 MW
McKendry	2002	30	Gasifier
Gustavsson and Madlener	2003	30	Combustion
Gustavsson and Madlener	2003	43	Combustion
la Cour Jansen	2003	24	
Yoshida et al.	2003	19–26	Combustion
Yoshida et al.	2003	16–30	Gasifier
Benetto et al.	2004	22	
Corti and Lombardi	2004	35	Gasifier
Siewert et al.	2004	35	Foster Wheeler high efficiency
Franco and Giannini	2005	15–30	Small to lg, depends steam temp
Ahrenfeldt et al.	2006	25	Wood to electricity
WEC	2007	20	

viable. Plants handling over 1000 dry tonnes per day would be competitive with coal if there is enough wood available. According to other authors, such as Koh and Hoi [27], it is unlikely that there would be sufficient wood available to meet this target sustainably.

4.2. Efficiency

Efficiencies of energy conversion from biomass vary widely across different technologies. This is an area under intense development, with many new, highly efficient technologies emerging.

Table 3 [10,11,15,29,35,38,40,48,54,57–67] summarises efficiencies found in literature. Combined cycle gasification processes show the greatest efficiencies at up to 43% [40]. The average efficiency of all technologies is 27%. There are diminishing returns from efficiency improvements, as small improvements at low efficiencies significantly affect profit margins, while at high efficiencies large improvements are necessary for the same gain [36].

As process efficiencies improve, greater attention will need to be given to efficiencies of cultivation (if applicable), collection and transportation of fuels. Improvements in this area will allow for significant price reductions.

4.3. Greenhouse gas emissions

Power production from biomass is often said to be carbon neutral. In some instances it is claimed that carbon sequestration to plant and soil, along with non-invasive farming methods make biomass electricity carbon negative, that is, less carbon is emitted than is removed from the atmosphere overall [15]. Many authors assert carbon neutrality, with emissions from combustion balanced by carbon capture of the next crop [50,68–71]. There is inevitably some fossil fuel usage not balanced by this equation, resulting from fertiliser, cultivation, collection and transportation. According to some authors, harvest methods that remove vegetation at or above soil level, leaving roots in the soil, leave sufficient carbon to balance all other emissions and maintain carbon neutrality [50,69–70]. Mann and Spath [72] claim net carbon negativity, since the combustion of biomass avoids anaerobic decomposition that results in methane emissions.

Table 4
Full life cycle carbon dioxide emissions from biomass power production.

Year	Author/s	Year	gCO_2/kWh	Comment
1998	Faaij et al.	1998	24	
1999	Norton	1999	30–40	
2003	Gustavsson and Madlener	2003	48	steam turbine
2003	Gustavsson and Madlener	2003	37	CC
2007	Chatzimouratidis and Pilavachi	2007	58 eq	
2007	Styles and Jones	2007	131 eq	miscanthus
2007	Styles and Jones	2007	132 eq	SRC willow

*eq denotes CO_2 equivalent in these values.

In most cases, authors find that electricity generation from biomass produces low net carbon emissions, mostly in the form of carbon dioxide, as shown in Table 4 [37,40,73–75]. Other greenhouse gases, such as methane and nitrous oxide are emitted in smaller amounts (2% or less of total emissions [76]). Where emissions include methane and nitrous oxide, figures are reported as carbon dioxide equivalent, or CO_2eq. The average carbon emission in Table 4 is 62.5 gCO_2/kWh. The highest emission, 132 gCO_2eq/kWh [75] is less than one third of the lowest natural gas and one fifth of the lowest coal fired power station emissions proven at present.

Wihersaari [76] calculated the minimum greenhouse gas reduction when substituting biomass in the place of fossil fuels at 74%, up to a maximum of 98%.

The calculation of carbon emissions can be complex, particularly when land clearing and soil carbon balances are included. If not produced sustainably, biomass generated electricity can actually emit more carbon dioxide per kilowatt hour than fossil fuels [15]. Biomass impacts are negative when native vegetation is removed for establishing an energy crop plantation. The establishment of such biomass crops is not renewable as its use as a fuel results in significant net carbon dioxide emissions [77]. For this reason, carbon emissions must include land clearing, deforestation and soil emissions [78]. Changing land use patterns can also affect greenhouse gas emissions. Highest emissions are seen where grassland and broadleaved forests are converted to arable cropland [79].

In dedicated energy crop cultivation, crops that grow with the least maintenance requirements, in particular little or no fertiliser, and highest energy densities, give the lowest emissions. This is of particular importance as nitrous oxide has a much higher global warming potential (GWP) at 298 than carbon dioxide, with a GWP of 1 or methane with a GWP of 25 [80]. Also an important consideration in dedicated energy crops is optimisation of harvesting time. Van Belle [81] showed that an increase in the diameter of wood residues being chipped from 4 to 16 cm reduced the carbon emissions per megawatt hour by a factor of seven.

The consideration of carbon storage in soils is also essential. There is over 1200 Gt of carbon stored in the world's soils, in comparison to the 550 Gt carbon stored above ground (mostly in trees) [78]. Modern farming methods rely on carbon sequestration to soil in their carbon balance and take measures to prevent the loss of this carbon, such as using no-dig cultivation.

According to Tampier et al. [19], crop yield is the largest influence on greenhouse gas emissions. Higher crop yields give larger carbon savings due to the carbon in the crops. Transportation does not add greatly to carbon emissions. Process emissions, while significant, are easily balanced by the fossil fuel displacement through biomass use. Dornberg et al. [7] also found that

Table 5
Emissions from alternate fuels, sources and technologies (Galbraith et al., 2006) [82].

Fuel	CO_2eq/kJ
UK electricity grid 1996	160
Straw combustion	63
SRC woodchip combustion	21
FR woodchip combustion	19
SRC woodchip pyrolysis	14
FR woodchip pyrolysis	12
SRC woodchip gasification	9
FR woodchip gasification	8

increased crop yields reduce greenhouse gas emissions. In their study using different crops, the most greenhouse gas friendly crop was found to be hemp grown in the Netherlands.

Technology choice impacts emissions, with pyrolysis and gasification showing significantly lower emissions than direct combustion and gasification slightly lower emissions than pyrolysis [82]. This is highlighted in Table 5 [82], also showing the difference in emissions from alternative fuel sources. Straw shows the highest emissions, while emissions from forest residues (FR) are always lower than emissions from dedicated short rotation energy crops (SRC). Although emissions from straw combustion are much higher than for other bio fuels, they are still less than 40% of the standard UK grid emissions for 1996.

4.4. Water use

Horticulture has significant water requirements [20] therefore, biomass will have a higher overall water use than coal. There is also high levels of water pollution from the use of pesticides and fertilisers [20]. Significant amounts of water are used during the cultivation, harvesting, transportation and processing of biomass. Berndes [59] gives a net water use on lignocellulosic bioenergy crops of 50 Mg/GJ of energy in the crops.

Because the technology for processing is essentially the same, cooling water for biomass based power plant operation requirements is similar to coal based power plants at 78 kg water/kWh of electricity [10].

4.5. Availability

The sustainability of biomass resources is dependent upon the rate of regeneration versus the rate of consumption, including non-energy demands [14].

The availability of feedstock is problematic for large scale generation. Crops are cheaper when waste products are used, however, high demands on wastes will outstrip supply, increase prices and traditional waste streams then become primary products. Due to resource constraints, many biomass plants operate for limited time periods, while feedstock is available. This severely limits the possible penetration of the biomass technology. For example, Matsumura et al. [83] explored the possibility of using Japan's main agricultural waste, rice straw and residue, to produce electricity and found that supplies would only be sufficient to operate a plant for 2 months per year.

Where dedicated energy products are grown, they compete with agriculture for space. Continual population growth rates are already causing food supply pressures and increasing starvation rates, making this competition highly undesirable.

Novel ideas for feedstocks are continually under development. For example, the Northern Territory government is helping to establish a pilot plant producing electricity from the environmentally damaging mimosa weed (*mimosa pigra*). The perceived benefits of this project are the control and eventual eradication of mimosa as well as remote area access to electricity [84].

It has been estimated by IEA Bioenergy [85] that there is a global potential for electricity production from biomass as high as 200 EJ/year. Kaygusuz [86] gave an estimated potential of 270 EJ on a sustainabile basis, significantly higher than the sustainable potential of 100 EJ/year given by Parikka [87]. It must be noted that even the lowest of these values, 100 EJ/year, still represents 30% of the global total energy consumption for 2004. There is significant room for increased utilisation of this resource. The CEC [23] calculated the long-term potential of bagasse at 7800 GW/year.

It is the opinion of the CEC [23] that biomass in stationary energy will almost always be from recovered wastes/by-products of higher value processes. Supply will be subject to the long-term viability of the primary product. Australia has a long-term potential of 50 TWh/year from agricultural wastes and 5 TWh/year from wood related wastes [23]. The long-term potential from grain crop residues, primarily cotton and wheat, is 47 TWh/year [88].

Fertilisation impacts are a function of harvest intensity and short rotation periods. Ash fertilisation may alleviate nutrient losses. Protecting organic layers in soil from disturbance and compaction helps to reduce runoff that causes stream and waterbody contamination by soil and silt [15]. Poplar short rotation forestry with a 2-year cycle yielded 16 dry Mg/ha/year with CO_2 emissions 7330 kg/ha/year, mostly from diesel fuelled machines. Fertilisers cause ammonia, methane and nitrous oxides emissions and groundwater pollution by acids and nitrates [89]. Toonen [90] studied *miscanthus* and received yields of over 20 t/ha with a net energy of 17 GJ/tonne produced. They found a long harvest window and low input of fertilisers and pesticides.

4.6. Limitations

Biomass use is resource and land constrained. The most productive crop land is agricultural pasture, otherwise used to produce food. In areas where soils are less ideal, crop yields are lower, sometimes to the point where the energy density is too low to be economical.

Crops must also be able to grow with minimal maintenance, including watering, fertiliser, pest and disease control. High maintenance requirements reduce the environmental benefits and increase carbon emissions and costs.

Abbasi and Abbasi [20] found that forest products have a higher economic value per kJ in their original form than when converted to heat or gaseous energy.

The highly variable nature of the biomass feedstocks causes complications. A product such as coal is carefully monitored and maintained at steady calorific and ash levels, allowing for steady process control and minimising fouling. Biomass does not allow the same control, even when using the same crops significant variations can be seen. The combustion of biomass also causes high levels of boiler fouling and corrosion [33].

Jungfeng and Runqing [91] concluded that biomass supply by energy crop cultivation cannot match full biomass demand, even if all feasible lands were developed.

4.7. Land use

Land used for biomass growth will often compete with food crops, forest and urbanisation, however, in some situations, biomass growth can be used to rehabilitate degraded or marginal soil. For example, the mallee plantations in Western Australia are successfully helping to resolve salinity problems where other plants could not survive. A pilot plant is developing ideal conditions to produce electricity from this tree [92,93]. Where environmental benefits are shared between several areas, economics should improve with the respect to electricity price

allocation. In the instance of Mallee eucalypts, the cost of environmental rehabilitation of the site should be accounted separately to the electricity cost. The San Antonio sugar mill established eucalyptus plantations on degraded soils and on soils that are uneconomic to cultivate common agricultural crops [94].

Fthenakis and Kim [95] compared the land occupation of different electricity generating technologies and found electricity production from willow has significantly the highest land transformation of any technology, at over 12500 m^2/GWh, while all other technologies were below 4500 m^2/GWh.

The allocation of valuable agricultural land and the destruction of natural forestry for energy crops growth is unsustainable. These situations should always be avoided and other alternatives sought.

4.8. Social impacts

There is a wide range of social impacts arising from the production of electricity from biomass. The extent of the impact will depend on the type of crop, how and why it was cultivated, the technology used to produce the electricity and how that electricity is distributed.

Food competition is ultimately the key social issue to be addressed. In many cases, energy crops compete with food crops for valuable agricultural land. To avoid this competition, energy crops need to be grown only on agricultural land not used for food crops.

Along with agricultural land, forests are an essential site for biomass crop growth. The removal of wood waste from forests can be partially compensated by returning wood ash, rich in mineral nutrients and counteracting acidification, however, nitrogen and organic matter are lost, the effects of stump harvesting and loss of biodiversity are not balanced [96]. Møller [96] also recommends that dead wood of a large size should be left as habitat for wildlife. The loss of habitat and biodiversity are key influences on the lack of public acceptance and support for the use of native forest residues, which are the main available biomass resource [97]. There is the general public perception that biomass power is not environmentally friendly [16]. Even scientific authors, such as Miranda and Hale [98], conclude that natural gas shows more favourable combined economic and environmental costs than biomass technology. IEA Bioenergy [15] conclude that the increased productivity of short rotation crops over forestry creates a smaller physical footprint, which is an important consideration.

Direct labour inputs for wood biomass are two to three times greater per unit energy than for coal [20]. There is also an increased labour requirement for construction, operation and maintenance. The employment generated by the production of electricity from fuel oil is 15 person.yr/MW.yr, compared to 32 person.yr/MW.yr for biomass [46]. More occupational injuries and illnesses are associated with biomass in agriculture and forestry than with underground coal mining, oil or gas extraction. Agriculture has 25% more injuries per man day than all other private industries [20]. If the safety of the agricultural sector could be improved, this would become a lucrative employment opportunity.

Taking waste wood from poor communities may remove self-sufficiency in areas where wood fuel is their only source of heating. Efforts must be made when establishing biomass sources to ensure competing users are not disadvantaged by biomass removal.

Comparing biomass with fuel oil, emissions of CO_2 and SO_2 equivalents are, respectively, 67 and 18 times lower [46]. With adequate flue gas cleaning and particulate removal, biomass power generation could be a much cleaner option than alternate fossil fuel technologies in terms of all pollutants.

5. Conclusions

The generation of electricity from biomass faces various environmental, technological and social challenges. Electricity price, efficiencies, greenhouse gas emissions, availability and limitations for biomass produced electricity are currently favourable, when compared with the other energy generation options, however, significant attention must be given to reducing the land and water use and, the social impacts of biomass power generation before sustainability can be achieved.

Sustainable power production can be achieved by growing hardy crops on marginal or otherwise unusable land, such as seen in Western Australia with the mallee tree or Nicaragua with eucalyptus. Integrated solutions like bagasse are also sustainable as the fuel is a waste product directly generated and reused on-site, reducing land use, water use and social impacts. The least sustainable biomass generation example occurs when energy crops compete with food crops or when energy crops are grown using high amounts of fertilisers.

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